Quark Propagation Through Cold QCD Matter

A Letter of Intent to the Jefferson Lab Program Advisory Committee

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Introduction

Context

Over the past two decades, quantum chromodynamics (QCD) has become established as the component of the Standard Model describing the strong interaction. A growing trend within the field of nuclear physics has been to attempt to connect observables in hadronic and nuclear systems with this theory, which is presumed to underlie their behavior.

QCD has had numerous successes in describing phenomena in the domain where the strong coupling constant is sufficiently small such that perturbation theory can be employed. In this regime there are no known failures of the theory. Further successes indirectly attributable to QCD have been obtained through the use of effective field theories in the low-energy, non-perturbative domain. These simpler theories are constructed to retain critical features of QCD, such as its symmetries. This approach has been applied to successfully describe a wide range of phenomena.

The frontiers of QCD in nuclear physics include lattice calculations of observables in relativistic heavy-ion collisions and in single-hadron systems, and making contact with simpler successful models such as the constituent quark model or the flux tube model, below the energy scale addressed by pQCD. Models based in varying degrees on the fundamental theory have been applied to finite nuclei to describe high-energy interactions of electrons and protons with these systems in the non-perturbative regime. While a rigorous description of these interactions is unlikely to be obtained in the near future, some successes have already been enjoyed[1].

Quark Propagation

A basic feature of high-energy nuclear processes is the propagation of quarks through nuclear matter. This is of fundamental importance in ultra-relativistic heavy ion collisions, in high-energy proton-nucleus reactions, and in high-energy lepton-nucleus interactions. The competing processes include quark energy loss, hadronization, and color transparency[2,19]. Hadronization is intimately linked to quark confinement, and a characterization of the hadronization process is likely to provide important insights into the nature and origin of confinement, a major focus of QCD nuclear physics. Quark energy loss occurs through two processes: collisional losses and through gluon radiation, the latter of which is thought to overwhelmingly dominate for hot nuclear matter[2]. The process of multiple scattering brings with it the phenomenon of multi-parton correlations, which may be accessible experimentally via signatures such as transverse momentum broadening[6]. The process of gluon radiation by quarks is strongly influenced by the local color fields in the nuclear environment, which are in turn strongly influenced by the phase of the surrounding nuclear matter. This makes quark energy loss an important probe of nuclear matter phases, as well as a tool to investigate the color structure of finite nuclei.

The mechanisms for energy loss of a fast quark propagating through QCD matter are similar to those responsible for the electromagnetic energy loss of a charged particle in matter[2]. In QED, it is possible to derive a precise expression for the energy loss of charged particles traversing ordinary matter[3], in spite of the fact that the matter is a complicated many-body system for which general solutions are impossible. In QCD it should also be possible to ultimately make precise calculations which can be compared with meaningful measurements, without a complete solution of the many-body QCD system. This has already been accomplished to a significant degree in perturbative QCD, as a result of intensive research activity by a number of workers over the past decade[4,15,18,19,20].

Proposed Measurement

In this letter-of-intent it is proposed to characterize quark hadronization, partonic energy loss and multi-parton correlations through a systematic investigation of semi-exclusive high-energy electron scattering off a series of nuclei of varying size. Outgoing hadrons will be analyzed in a large-acceptance spectrometer capable of detecting multiple particle final states with good particle identification and momentum analysis. A comparison of the energy of the virtual photon (ν) with the energies of outgoing hadrons (E_h) can be made over a wide range of momentum transfer (Q^2) and ν for a series of nuclear thicknesses (L). The transverse momentum p_t will also be determined at some level of accuracy. One useful quantity for these studies is the hadronic multiplicity ratio, defined by:

$$^{h}R_M(A) = \text{(normalized hadron rate for nucleus A)/(normalized hadron rate for deuterium)}$$

which is a measure of the tendency of the struck quark to interact with the nuclear medium. In this context the normalization is such that the hadron production rate is calculated per nucleon and per deep inelastic scattering event.

A variable which has utility in identifying quark energy loss and hadronization is the ratio of the leading hadrons' energies to the energy of the virtual photon (assumed to be the initial energy of the struck quark):

$$z = E_h / \nu$$

A systematic study of the hadronic multiplicity ratio ${}^{h}R_M$ as a function of Q^2, ν, z, p_t, and <L> for emitted pions and protons (and possibly kaons) will characterize quark hadronization and energy loss in larger nuclei for sufficiently high Q^2 and deep inelastic kinematics. In a large-acceptance, multiparticle spectrometer, it will be feasible to simultaneously study a number of other quantities which may be useful in quantifying energy loss, multi-parton correlations, and hadronization. For example, a straightforward measurement of the transverse momentum broadening of the mini-jet ejectiles may be feasible and has been predicted to directly probe quark-gluon correlation functions[6] (see also Ref 20). Further information on transverse momentum broadening can be obtained by studying two-ejectile events such as $\gamma^* A \rightarrow \pi^+ \pi^- AX$ in the appropriate kinematic region, looking at the azimuthal angle ϕ^* between the two. Transverse momentum broadening will be seen as a broadening in the ϕ^* distribution which has a nominal maximum at 180^o; this effect, which can be characterized as a function of Q^2, ν, z, and <L>, is intimately related to the parton energy loss and multi-parton correlations. Kaon measurements may also be feasible in some kinematics, which provides additional information related to strange quarks, i.e., hints on the flavor dependence of these quantities. For any of these measurements it will also be possible to study the properties of correlated particles in events which include mini-jets due to the multiparticle acceptance of the spectrometer. Important information on hadronization dynamics may be obtained from analysis of heavy recoils or lower-energy particles which are correlated with the leading hadrons[12,13]. The Q^2 and x dependence will help to probe the transition from the vector meson dominance region to the quark knockout mechanism[12].

It has been suggested that an infrared-stable, first-principles perturbative QCD calculation can be performed for heavy/light quark production ratios, such as D/π yields[11]. A systematic study of such ratios as a function of the variables mentioned above, such as ν and <L>, would be of great interest and would impact the understanding of quark propagation, although the measurement, which is near production threshold, would be an experimental challenge (and may ultimately not be feasible). Another suggestion of an interesting ratio to study is that of phi production to rho production; the idea is that if the meson is formed within the nucleus, the ratio will vary with increasing <L> because of a smaller phi-nucleon interaction[13]. Both of these ideas will require further study to determine experimental feasibility and sensitivity, unlike most of the measurements suggested above, which are entirely straightforward. However, they are appealing, and deserve further study. In any case these reactions are likely to be contained in the data set, since minimal trigger conditions will be imposed. Other open questions may also be addressed by this data set[16,21].

The hadron formation time ${}^{h}t_{f}$ is defined as the mean time elapsed between the quark being struck and the formation of a leading hadron. Its functional form has not been determined from a fundamental theory. Models of varying degrees of sophistication have assumed or derived forms of this quantity which depend on up to three variables[5,17]. The proposed measurement may be sufficiently sensitive to constrain the functional form of this basic quantity.

A lower-energy, exploratory portion of this series of measurements could be carried out with the 6 GeV beam at CEBAF using the CLAS spectrometer. The primary set of measurements can be carried out with the 11.5 GeV beam from an energy-upgraded CEBAF. Even higher energy measurements at the proposed Electron-Ion Collider would also be of interest for the largest nuclei and highest energies.

Previous Measurements

There have been recent measurements related to quark hadronization or energy loss. Measurements at Fermilab with 800 GeV protons on a nuclear target used the Drell-Yan process to study quark energy loss effects; a range of values (from 2.7 GeV/fm down to a small fraction of a GeV/fm) was obtained for the energy loss, depending on the assumptions of the analyses, however, the issues now appear to be better understood (for a comprehensive discussion, see Ref. 7 and references therein, including a discussion of the relative merits of the Drell-Yan and deep-inelastic measurements of partonic energy loss). An advantage of the proposed measurement over this one is that the energy loss is much closer in magnitude to the beam energy, increasing the sensitivity of the measurement. A second advantage is the relative simplicity of the virtual photon probe (aside from fluctuations into vector mesons) compared to the proton, which is a composite object with its own extensive quark and gluon fields. The complexity of the probe may introduce ambiguities into the interpretation of the data. For instance, it has been suggested that the gluon spectrum of the proton is modified within the nuclear medium, a phenomenon referred to as gluon depletion[8] and gluon enhancement has also been suggested[23]. It will also not be necessary to separate out nuclear shadowing with the proposed measurement, as it has been with the analyses of the Fermilab data; this effect will be a consideration at RHIC and LHC[14]. A lower energy measurement has been proposed, which would provide a second data set. The second data set would be very beneficial; taken together with the e-A measurements, it would allow a more comprehensive study of energy loss and hadronization issues.

A second measurement at HERMES used a positron beam of 27.5 GeV incident on a nitrogen target[5]. This measurement, like the present proposal, has the advantage that the virtual photon probe permits a relatively simple interpretation of the data since at sufficiently high Q^2 it predominantly interacts only with a single quark, i.e., the initial state of the interaction has a high probability of being a quark of energy ν. The Hermes measurement appears to be of sufficiently high energy to observe the region where the quark hadronizes after it exits the nucleus.

The measurements proposed here should have much better statistics, broader kinematic and multiparticle coverage, a wider range of nuclear sizes, and will extend to lower energies to include more of the regime where the quark hadronizes within the nuclear medium. The improved statistics will permit study of the quantities discussed above as a function of multiple variables rather than integrating to distributions of a single variable, which will provide significantly more information, and will permit these studies with a higher momentum transfer cutoff (the quoted study included data down to 1 GeV^2). The comparison of the proposed experiment to the Hermes measurement will provide a valuable cross-check and will give a complete picture of the behavior of ${}^{h}R_M$ over a wide range in ν for ${}^{14}N$. A plot of the hadronic multiplicity ratio for $z>0.2$ from Ref. 5 is shown in Fig. 1, together with a number of parameterizations which assume a variety of functional dependencies for the hadronization time. (For an explanation of the curves and references to the data shown, see Ref. 5.) A naïve expectation is that at sufficiently small ν the ratio will become much smaller due to the quark hadronizing within the nuclear medium[19]; once this occurs, the interaction cross section becomes large, causing the ratio to deviate significantly from unity. This turnover should occur at higher values of ν for heavier nuclei. The asymptotic deviation from unity can be related to the energy loss within the nuclear medium. Some models were found to give good agreement with the data[19].

It should be noted that more measurements and analyses are underway at Hermes, and luminosity upgrades are also under consideration. A complete picture of the complementarity of the present proposal with the Hermes data will be important to form in the full proposal, however, it is safe to say that the proposed measurement will be able to make a significant and unique contribution. Also, noting the large discrepancy between the SLAC data and the Hermes data seen in Fig. 1, it is always beneficial to have some regions of overlap from different experimental efforts in these exploratory measurements.

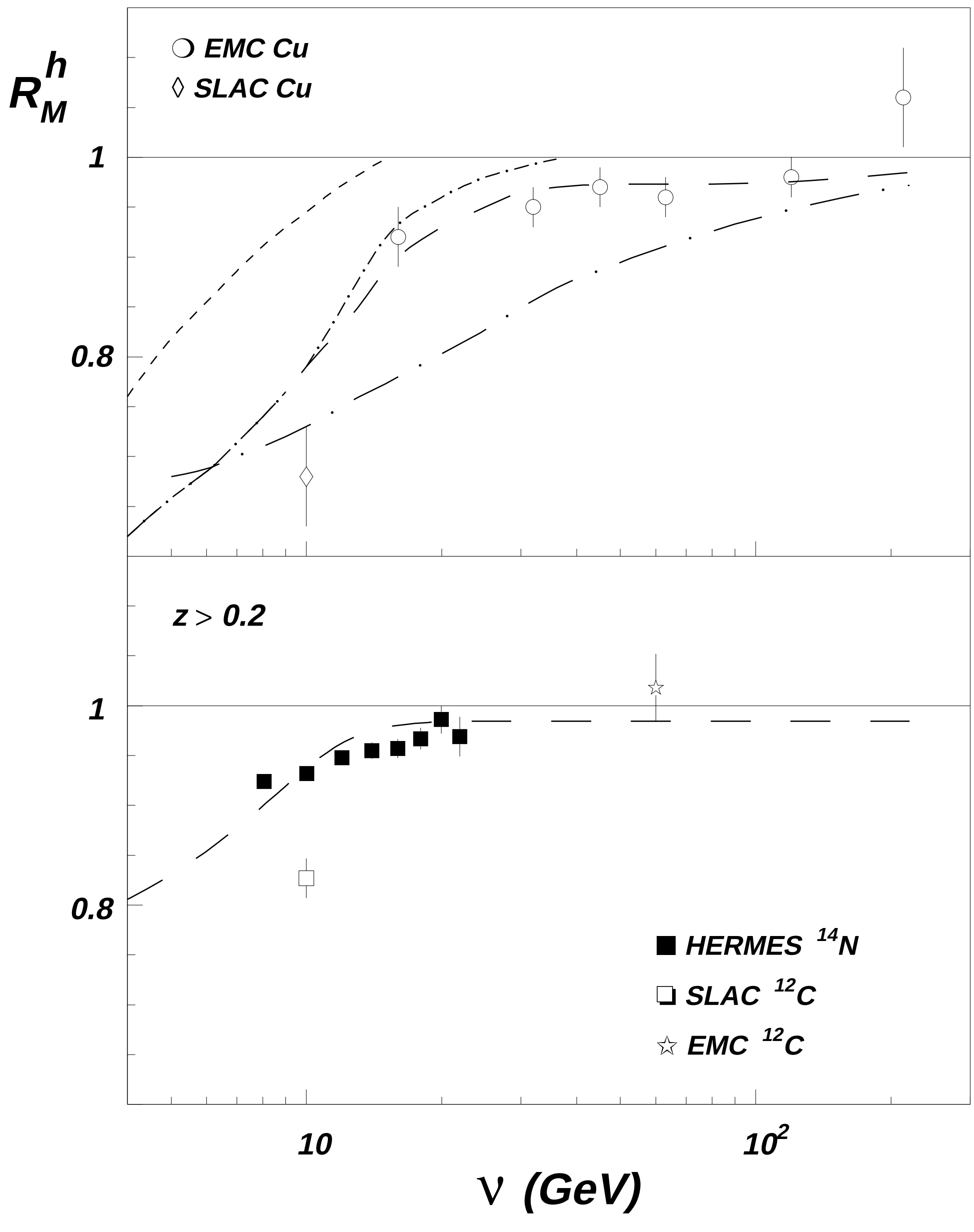


Figure 1. Existing data from several previous measurements of the hadronic multiplicity ratio, along with curves from theoretical models. (Plot taken from Ref. 5; for further discussion of the data and curves, see this reference.)

Scientific Motivations

Tests of Predictions

There exist a number of models of quark transport through nuclear matter which have varying degrees of contact with QCD. There have also been recent perturbative QCD calculations. A number of these models and calculations have already been cited in references 1, 2, 4, 5, 6, and 7, and further references may be found within those papers. There are many scientific issues which may be addressed by comparison of the predictions of these calculations with the kinds of data here proposed to be measured. One topic addressed is an improved understanding of gluonic radiation processes, through the radiative energy loss mechanism[21]. Another is an improved understanding of the nature and dynamics of confinement through measurements of hadronization parameters such as hadronization time as a function of several variables. A third is to provide an experimental testing ground for refining QCD-based models which is somewhat distinct from and complementary to spectroscopy, where a large program is already planned. The measurements proposed clearly will explore the role of quarks and gluons in nuclei. Most of these topics have been identified as ‘key issues in hadronic physics’ in a recent paper of the same name[9].

Phases of Nuclear Matter and the Gluonic Content of Nuclei

A major thrust of modern nuclear physics is to determine the properties of the phases of nuclear matter. The highly successful advent of RHIC measurements and the planned heavy ion program at the LHC attest to the degree of interest within the national and international community in this subject. One of the earliest indications of the possible formation of the quark-gluon plasma at RHIC has been hints of “jet quenching”, an idea introduced a decade beforehand[4]. Jet quenching refers to a dramatic increase in the energy loss of quark or gluon jets and their associated hadrons within a quark-gluon plasma relative to normal (‘cold’) nuclear matter.

An essential ingredient in constructing a theoretical interpretation of the RHIC data is partonic energy loss, and, especially at lower energies, partonic hadronization. Relatively small changes in the assumptions concerning quark transport through nuclear matter can produce significant changes in some observables. Obtaining unambiguous information on quark transport in ‘cold’ nuclear matter will, in combination with precise measurements from RHIC, provide an important benchmark needed to identify and characterize the quark-gluon plasma.

While the planned complementary program of p-A collisions at RHIC will provide important information on quark transport, information from electron scattering can provide complementary insight which relies on a different set of assumptions. Much may be learned from a systematic comparison of the two approaches. The combination of data from this experiment and the p-A experiments has the potential to provide significant insight into several fascinating topics such as the modification of the proton's gluon distribution in the nuclear medium[8,23] or the potential to observe effects related to gluon saturation[10]. It may be possible to derive information relevant to existing predictions for the behavior of the nuclear gluon distribution[14].

Experimental Method

Summary

The measurements will be performed on a range of target masses spaced appropriately to obtain approximately equal energy loss increments. Events with relatively large Q^2 will be selected in order to assure the interaction is primarily with isolated (~constituent) quarks and to permit comparison to perturbative calculations when practical. Deep inelastic scattering will be selected (W>2.2 GeV) to ensure the validity of the partonic picture. Leading charged hadrons will be selected and the hadron multiplicity ratio ${}^{h}R_M$ will be studied as a function of Q^2, ν, z, p_t, and $\langle L \rangle$ for pions and protons, and possibly kaons. Other kinematic quantities will also be studied, such as the evolution of the transverse momentum broadening with the variables z and ν for single mini-jets and 2-charged-pion events. Detailed simulations will be required to determine the experimental sensitivity of the measurement of the transverse momentum, however, some calculations have predicted sizable effects[6].

Experimental Apparatus

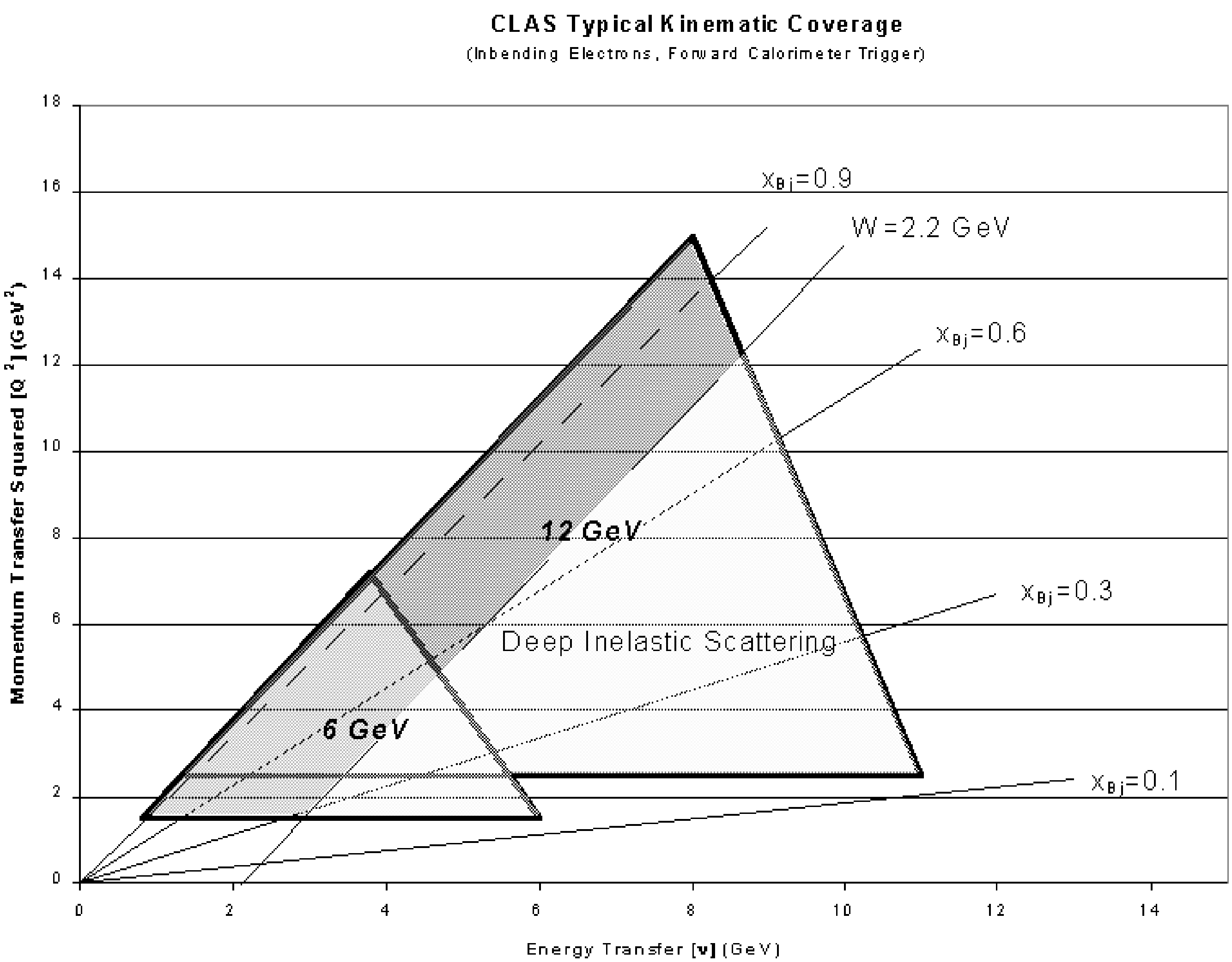
The CEBAF Large Acceptance Spectrometer (CLAS) is well suited for systematic studies such as are proposed here. Several of its properties are of particular value. First, the capability of detecting multiparticle final states in coincidence measurements with good charged particle identification and momentum resolution allows multiple leading particles to be identified and offers a very large kinematic range of measurement for each particle. Neutron identification is also available, including momentum measurement at lower energies. The spectrometer has a large acceptance particularly for events at higher momentum transfers. A sketch of the kinematic coverage of the spectrometer with 6 GeV and 11.5 GeV beam is shown in Fig. 2. For each of the two beam energies, the available kinematics indicated is covered simultaneously in a single measurement. Only electron (inclusive) kinematics are shown for a standard configuration; in exclusive kinematics for the studies mentioned the coverage will be more limited, and will depend on the reaction, target location, and other details. Routine use is made of cryogenic liquid targets and solid foil targets. Typically a single target is used, however, a simultaneous combination of one or two cryogenic liquids and multiple solid targets is also possible and has previously been used for experiments with special requirements. The acceptance for inclusive events is much greater than 50% at the highest momentum transfer for a given beam energy, and for exclusive events a range from 10% – 50% is typical, depending on the details of the kinematics. A luminosity of 10^{34} cm^{-2}s^{-1} is available with the 6 GeV beam, and 10^{35} cm^{-2}s^{-1} is planned for the 11.5 GeV beam. These luminosities are one and two orders of magnitude greater than the Hermes measurement, respectively. In combination with the large detector acceptance, this should permit sufficient statistics to be accumulated so that dependencies on multiple variables can be determined, rather than summing over all but one variable as was generally necessary with the Hermes data. A non-restrictive trigger, as is typically used with CLAS running, will be employed to minimize the trigger dependence on the data set.

It should be noted that at 6 GeV, one is only in the threshold region of where the simple picture of a propagating, hadronizing quark is valid. However, measurements in the transition region with 6 GeV beam may provide an important baseline for the higher energy measurements, characterizing the breakdown of the simple picture. For the highest ν accessible it may provide a limited but very interesting early data set for comparison with the Hermes data and the Fermilab data; obtaining this data in a few-year time frame could have an important impact on the early RHIC analyses. Even phenomena at lower ν may turn out to be important at RHIC; since the energy loss is expected to be very large in the quark-gluon plasma, hadronization at lower parton energies could still be a non-negligible component. A detailed study is needed to determine the practicality and impact of a measurement at 6 GeV.

Target Selection

Approximately five to seven targets will be chosen. The expected dependence of the quark energy loss is that the collisional energy loss is proportional to the distance through the nuclear medium L, and the radiative energy loss depends on the square of the distance through the nuclear medium, L^2. The nominal target choices based on these considerations would be equally spaced in energy loss to the extent the relative proportion of these two effects can be estimated. However, consideration will also be given to matching the targets from previous experiments and the planned p-A program at RHIC. For instance, deuterium and nitrogen would be used for compatibility with the Hermes data. Existing data from CLAS will be used where possible. An additional consideration is that for the initial survey at 6 GeV, hadronization will occur outside the nucleus only for lighter nuclei; including more of these would be of interest. A detailed analysis of the issues is planned.

Figure 2. Kinematic coverage of CLAS for electrons (inclusive kinematics). The two triangles represent the kinematics available in a single typical setting for 6 GeV and 11.5 GeV beam. The shaded region below the line labelled "W=2.2 GeV" indicates the deep inelastic kinematics.



Conclusions

A systematic study of high momentum transfer, semi-exclusive measurements on a range of nuclei has been proposed. These experiments focus on characterizing quark transport through cold QCD matter, particularly in the areas of partonic energy loss, hadronization, and multi-parton correlations. The experimental requirements are well-matched to the capabilities of the CLAS spectrometer.

This Letter-of-Intent addresses topics of great current interest and relevance to high-energy electromagnetic nuclear physics and to relativistic heavy ion nuclear physics, both the A-A and p-A programs. It has direct connections to the experimental programs at Jefferson Lab, RHIC, LHC, and the proposed EIC. Strong theoretical input from a variety of viewpoints is critical to achieving a proper understanding of this data; the list of theoretical collaborators included is an impressive collection of most of the expert practitioners in the field, and their contributions will be crucial to the success of the experiment. It is intended that a full proposal will be developed in the near term, if encouraged. It is hoped that these measurements and their interpretation will open a new and important window on QCD dynamics.

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